Library, L.M.A.L.

3 1.5.0
3 7

TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 412

A I R C O O L I N G

AN EXPERIMENTAL METHOD OF EVALUATING THE COOLING EFFECT OF AIR STREAMS ON AIR-COOLED CYLINDERS

By J. F. Alcock

From "The Automobile Engineer," April, 1927

Washington
May, 1927

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

TECHNICAL MEMORANDUM NO. 412.

A I R C O O L I N G

AN EXPERIMENTAL METHOD OF EVALUATING THE COOLING EFFECT OF AIR STREAMS ON AIR-COOLED CYLINDERS.*

By J. F. Alcock.

It is no easy matter to estimate the cooling power of the air stream over an air-cooled cylinder. Theoretical treatment is generally impracticable owing to the complex nature of the problem, while direct experiment has proved very difficult except in the simplest cases. As a result the data available are very limited, a fact which has, in all probability, seriously retarded the development of the air-cooled engine.

In the following pages is described an experimental method which the writer has evolved for dealing with this problem, and some of the data obtained by its means. This method has the advantage of simplicity, both as regards apparatus and procedure, and affords data which are accurate enough to be of considerable practical value.

The conditions governing the transfer of heat from a heated surface to an air stream may be expressed by the formula:

$$H = K \Delta T,$$

where H is the heat transfer, ΔT the air-metal temperature

*From "The Automobile Engineer," April, 1927.

difference, and K a coefficient expressing the "cooling power" of the air stream over the surface.

This coefficient is, of course, a function of the velocity and of the nature of the air flow, and may also be a function of the heat flow or temperature. In fact, the above formula is merely a definition of the coefficient K.

Hitherto data on this subject have been obtained by two methods. In one case, a dummy cylinder or other object is placed in an air stream, and is maintained at a known temperature by some form of heating, generally electrical, in which the heat loss can be measured. H and T being known, one obviously has the cooling coefficient K.

This method is clearly suitable in a case, such as that of a radiator, where the total cooling effect is the important point, and where the heat loss from the test object can easily be measured. Applied to an air-cooled cylinder, it has the drawback that it only gives the average cooling of the cylinder, and ignores the equally important question of the distribution of this cooling in different parts thereof. Moreover, experimental difficulties limit this method to simpler forms than are normally used in practice.

The second source of information is temperature measurement in actual air-cooled engines. Valuable though these are, they have the following limitations:

1) They only give one variable out of three, and thus do not

tell the whole story. For example, a change in temperature may be due to a change in the heat dissipated, or in the cooling coefficient, or in both, and it cannot always be decided which is responsible.

2) An actual working cylinder must be used, and not a dummy.

The present method is intended not to supplant, but to supplement those above described. It is applicable to the most complex conditions, and can easily be used with dummy cylinders, etc., by means of which the possibilities of new designs can be explored at a low expenditure of time and money. It is by no means a "laboratory" method, since the apparatus is rugged enough for workshop conditions, and no great skill is required.

Briefly, the method is to explore the air stream around the object by means of a small metal "test piece," which is heated and allowed to cool in the air stream at the point where a reading is required. Knowing the surface area, and the heat capacity of the test piece, the "cooling coefficient" K can be calculated from the observed rate of cooling, and this coefficient is taken as applicable, relatively, if not absolutely, to the cylinder, etc., surface adjacent to the test piece. This, of course, involves some assumptions which might be difficult to defend theoretically, especially where, as is usually the case, the test piece has a form different from that of the actual surface to be cooled.

These assumptions will be discussed later, but experiment

appears to show that they do not, under ordinary conditions, lead to any serious error.

The principle involved in this method is not altogether new, being that of the "Katathermometer" used in medical research, but it has not, to the writer's knowledge, hitherto been applied to engineering problems.

Apparatus

The "cooling meter" generally employed is illustrated in Fig. 1. It consists of a bronze ball 3/8 inch diameter, into which are silver-soldered copper and constantan wires of 22 S.W.G. These wires lead up the stem of the meter, which is made as narrow as possible to avoid disturbance of the air flow, and thence by means of flexible leads to a galvanometer of any suitable type. The cold junction is arranged in the flexible lead about a foot from the handle, so as to attain the temperature of the air stream and to be unaffected by the warmth of the operator's hand. For a test the ball is heated by a spirit lamp or other convenient source of heat, and is then placed in the required position in the air stream. The time of cooling over some standard range of temperature is then measured, the range usually taken being 200 to 100 °C. above atmosphere, which is fairly representative of aircraft engine practice. From this time the rate of heat transfer and the cooling coefficient can easily be deduced. Preferably the initial heating is carried up

to say, 300 °C. to allow the heat flow to become steady before the actual reading commences.

A similar instrument has also been tried in which the ball is replaced by a flat copper plate, it being thought that, with such a surface, the conditions would more nearly resemble those of the ordinary radiating fin. This instrument, however, has up to the present been found to be less convenient in operation than the ball type, as small variations in the attitude of the plate to the air stream seriously affect the results.

The position of the stem does not seriously affect the results, so long as it is not "up-wind." With the stem down-wind, the cooling is some 3 to 4 per cent less than with the stem at right angles to the stream, this latter being normally the most convenient position.

Calibration of the Instrument

To calibrate the instrument, tests were carried out in an unobstructed air stream at speeds ranging from 5 to 110 M.P.H., also in "still air," i.e., shielded from draughts, but with free convection. It was, however, discovered that the cooling coefficient was not a function of the wind speed solely, but also of some other factor, apparently the degree of turbulence. Thus for two places 5 inches apart in the same fan stream, the cooling coefficients for the same wind speed, as measured by a pitot-tube, were found to differ by some 10 per cent.

Fig. 2 shows the results of two calibration tests, one made in the outlet duct of a centrifugal fan, and the other in one of the N.P.L. wind tunnels, the wind speeds being measured by pitot-tube. Somewhat unexpectedly the cooling rate in the wind tunnel is higher, for a given wind speed, than in the fan stream, though the turbulence is presumably greater in the latter case. The only theory that the writer can put forward to account for this is that, in the "turbulent" stream, the velocity at any given point may fluctuate considerably. The pitot-tube, in which the pressure varies as the square of the velocity, registers the "mean square" value, which is higher than the true mean velocity, while the cooling varies roughly as the 0.6th power of the speed, and thus gives low figures in a varying stream.

In both of these tests the temperature range used was 200 to 100°C. above atmospheric. The surface of the ball was maintained in a dull but smooth condition. If completely sooted, the loss goes up by about 0.5 unit in "still air." Calculation gives the radiation from a "black body" under these conditions as 2.0 units, so that the emissivity of the surface in its normal condition is about 0.75 of the black body figure, which agrees fairly well with other data for dull metal surface. Curiously enough, a nickel-plated ball, when slightly "browned" by use, appears to have an emissivity of about 0.6, which is rather high.

These curves can, however, be fairly accurately expressed by simple formulas, which are:

Wind Tunnel ... $K - K_o = 2.95\,V^{0.61}$

Fan Stream ... $K - K_o = 2.52\,V^{0.63}$

where H, H_o are the cooling coefficients at V M.P.H., and in "still air" respectively. The cooling coefficients are given in:

$$\frac{\text{C.H.U.}}{\text{sq.ft.} \times \text{hr.} \times {}^{\circ}\text{C.}\ \Delta T}$$

or

$$\frac{\text{B.t.u.}}{\text{sq.ft.} \times \text{hr.} \times {}^{\circ}\text{F.}\ \Delta T}$$

ΔT being the mean metal-air temperature difference during the test. These units are for brevity hereafter referred to as "cooling units." It should be remembered that this coefficient must be multiplied by the temperature difference to give the actual heat flow.

A test was made, at a fixed wind speed with various ranges of temperature, the results being shown in Fig. 3. It will be seen that the cooling coefficient attains a minimum at about 250°C., and increases at higher and lower temperatures. The whole variation, however, is not of any great significance, the difference between the greatest and least values being only some 8 per cent.

Applicability of Cooling Values Obtained by Cooling Meter to Actual Radiating Fins

As previously stated, this method aims primarily at giving relative values for the cooling under different conditions,

rather than directly applicable absolute values. It is, nevertheless, of interest to compare the cooling values so obtained with such data as can be directly obtained under actual working conditions. Fortunately, this can be done, somewhat roughly it is true, in the case of one of the cylinder heads tested, where the heat passed through a considerable depth of metal of known conductivity, so that the heat flow could be calculated from measurement of the temperature gradient. The mean fin temperature could also be calculated fairly closely, from the thermocouple readings taken at various points, so that an approximate value of the heat transfer coefficient can be obtained. Thus in two tests the figures in Table I were obtained.

Table I.

Heat flow C.H.U. per hour	Mean fin temperature above atmospheric (ΔT)	Fin area sq.in.	Cooling coefficient C.H.U. per hr. × ft. × °C. ΔT
6840	156°C.	132	48.1
6950	165°C	132	46.0

Wind speed 105 M.P.H.

With the cooling meter, figures were obtained at three places on the mid-level of the fins (See Fig. 9), "Y" in the front, "Z" at the rear in the "shadow" of the sparking plug, and "W" in the rear, but clear of the plug shadow. The values obtained at these points, with a wind of 108 M.P.H., are:

Point	Y	47.9
	Z	36.6
	W	45.6.

The conditions at "Z" are probably very localized, so that the average cooling coefficient would appear to be about 45 to 46 units, which agrees fairly well with the necessarily very approximate values of 46 and 43 obtained above.

Another case in which direct experiments have been made is that of honeycomb radiators. The cooling coefficient obtained in this case comes to 47.2 C.H.U. per ft. × hr. × $^{\circ}$C.ΔT for a radiator tube of $L/D = 6$, to which the head fins of this engine may be taken as roughly equivalent, in a 108 M.P.H. wind.

It appears, then, that the absolute cooling values obtained from the "cooling meter" are fairly representative of those obtained in practice under similar conditions.

Another factor to be considered in applying cooling meter data to actual practice is the effect of the variations in air temperature which occur in practice. The air at the rear of a working cylinder, for example, is hotter than in the front, having been heated in its passage past the cylinder. In cooling meter tests, however, which are most conveniently done with a cold cylinder or with dummies, this effect is not present, and the cooling values given will, therefore, in some cases, be too high. To discover the influence of this factor under the conditions obtaining in practice, the air temperature in the front and rear of an aircraft engine cylinder was taken, by means of a mercury thermometer, when the engine was running under load, on the test bed, the mean cylinder temperature being about 200°C. and

the air speed 105 M.P.H. The values recorded were:

Front of cylinder ... 36°C.

Rear of cylinder ... 47°C.

It is clear, then, that with high wind speeds, the correction needed for this temperature effect is small, but with lower speeds it may become serious.

Plate Instrument

Mention has been made previously of a modified form of instrument in which the test piece was in the form of a flat plate. This has not been used to the same extent as the ball type, since its sensitiveness to its attitude to the air stream renders it rather troublesome. It is, however, useful for close-quarter work among fins, etc. It gives readings of the cooling coefficient which are normally about 10 per cent less than those given by the ball type, this relationship being fairly well maintained under different conditions of flow. This is well shown in Fig. 4, which shows comparative tests made under identical conditions, on the air flow around a dummy cylinder, using both the plate and ball instruments.

Experiments Made with the Instrument

In the following notes details are given of some experiments carried out with this instrument. It is not claimed that they are comprehensive, but they exemplify the possibilities of the method.

With one exception all were made under test-bed conditions, that is, with the cylinder "blown at" by a fan. These, of course, are not of such interest as would be data gained under actual working conditions, but although these should not, in most cases, be impossible, there has hitherto not been any opportunity to carry out such tests.

Figs. 5 to 7 show tests on dummy cylinders of various sizes. These cylinders were made of tin plate, without fins, and carried at their upper end a "jig" by which the cooling meter can accurately be located both circumferentially and radially. The ball of the cooling meter was some 5 inches below the top of the cylinder, so as to be clear of any disturbance of the air flow due to the "jig." All the tests were made at a constant wind speed of 35 M.P.H., measured on the center line of the cylinder, while the standard temperature range of 200 to 100°C. above room temperature was used throughout. Readings were taken at every 15 degrees around the cylinder, with intermediate points in places where rapid changes were found, while check readings were taken every 30 degrees.

In Fig. 5 are shown three tests on cylinders having diameters of 2 in., 4.4 in., and 7 in., with a "radial clearance" - i.e., distance between ball center and cylinder surface - equal in each case to 0.2 of the cylinder diameter. Thus the proportions of the apparatus are the same throughout and only the scale varies. The three curves, it will be seen, are substanti-

ally similar in form, though with appreciable local variations, due probably to eddies. It would appear, therefore, that within this range of size, there is no serious "scale effect," though the variation between the maximum and minimum values is somewhat less with the 2-inch cylinder than with the others. Fig. 6 shows a similar series of tests, but with the same radial clearance of 0.4 in. throughout. In this case the curves are practically identical, except at the rear, where the cooling is much higher with the 2-inch cylinder.

Fig. 7 shows three tests on the 7-inch cylinder with increasing radial clearances. These differ very little, except at the rear, where the sudden drop in the cooling occurs farther to the rear as the clearance increases. The very sudden drop at 160 degrees with the largest clearance is rather remarkable. This part of the curve was checked at every 2 degrees, so that this rapid drop undoubtedly exists.

All these curves have a characteristic double-humped form, with maxima at 60 to 70 degrees, and at 130 to 135 degrees, the forward peak being, as a rule, slightly the higher. The drop from the rear peak to the "dead-water" region behind the cylinder is generally sharp, and in some cases extremely so. Generally, however, the cooling at the rear (180 degrees) is but little less than in the front, which is rather surprising. The average cooling, over the whole circumference, closely approaches

the value recorded at the cylinder axis with the cylinder removed.

Cooling fins in most cases modify these results to an appreciable extent. A typical series of tests was made on an aircraft engine cylinder 5.5 in. bore × 7 in. stroke. The cooling wind for this cylinder is supplied by a motor-driven fan through a louvered duct to steady the flow. The mouth of the duct is 15½ in. high and 12 in. wide, its location relative to the cylinder being shown in Figs. 8 and 9.

Table II.

Ball instrument. Fan R.P.M. = 980. Temp. range 200-100°C. above room. Mean cooling = 32.0 C.H.U./sq.ft. × hr. × °C. Δ T. Bracketed figures, % of mean.

A	B	C	D	E	
36.8 (115.0)	36.0 (112.5)	36.1 (113.0)	35.5 (111.0)	36.3 (113.5)	1
36.3 (113.5)	36.8 (115.0)	35.0 (109.5)	35.1 (110.0)	34.7 (108.5)	2
32.2 (100.5)	35.5 (111.0)	32.2 (100.5)	33.1 (103.5)	33.9 (106.0)	3
29.0 (90.5)	32.8 (102.5)	31.0 (96.5)	31.8 (99.0)	34.1 (106.5)	4
26.2 (82.0)	27.1 (84.5)	25.1 (78.5)	33.9 (106.0)	35.1 (110.0)	5
	21.4 (67.0)	23.1 (72.0)	30.8 (96.5)	33.7 (105.0)	6
27.2 (85.0)	29.4 (92.0)	30.8 (96.5)	28.6 (89.5)	34.5 (108.0)	7

The distribution of air flow over the mouth of the duct was investigated by means of the cooling meter, the results being

shown in Table II. From this it appears that the velocity increases fairly steadily from the bottom to the top of the duct. As the same tendency occurs in the case of a radial engine in the air, this characteristic is not harmful.

The cooling around the cylinder barrel was then investigated A plain cylindrical portion of the barrel, 2 in. below the top of the cylinder, and unobstructed by pipe-work, etc., was chosen, and readings taken from 0 degree (up-wind) to 180 degrees (down-wind) by stages of 11 1/4 degrees. The radial position of the ball was 1/4 in. off the fin tip, or 1 1/4 in. off the body of the cylinder.

Tests were made with four wind speeds, 41, 63, 83, and 108 M.P.H., these speeds being measured over the cylinder head, and the results obtained are shown in Figs. 10 and 11. The characteristic curves are substantially the same for all the speeds, there being a region of moderate cooling in the front of the cylinder, a maximum value at about 70 degrees, and then a falling off to a region of low cooling from 140 to 180 degrees. The sudden drop at about 120 degrees is very marked in all cases, and presumably this point is the beginning of the "dead water" or eddy region.

The effect of the fins, due presumably to their frictional drag, is to suppress the rear hump found with the bare cylinders, while accentuating, both in extent and in lack of cooling, the "dead water" region at the rear.

Tests were made at a few places at other levels on the cylinder barrel, and showed substantially the same characteristics. A curious point observed was that the exhaust pipes, which spring off the cylinder at an angle of 45 degrees, are not the cause of any "dead-water" region in their rear, the cooling immediately behind the pipe being practically the same as in the clear flow. Possibly this is due to their oblique attitude to the air stream, which gives them an effective section of elliptical form, which is more or less "streamline."

Cylinder Head

A dummy head was fitted to this engine for the purpose of these tests, having a more or less flat top carrying a number of cooling fins. The arrangement of these is shown in Fig. 9. Cooling tests were made at the points Y, Z, and W, at the mid-level of the fins, and at the point X, $1\frac{1}{2}$ in. above the fin tips, to give a "free wind" value for comparison. The figures obtained for these positions are given in Table III.

Table III.

Position	Cooling for wind speed, M.P.H.			
	41	63	83	108
X	31.0	43.6	46.4	53.0
Y	30.1	39.7	42.5	47.9
Z	19.0	25.5	28.0	36.6
W	24.3	33.0	35.5	45.6

It appears that where the flow is unobstructed, except by the fins, as in the W position, the cooling at the back is not much worse than at the front (Y). The position Z, however, is in the "shadow" of the sparking plugs, and this reduces the cooling considerably at this point.

In the tests recorded above, the cylinder was exposed to an otherwise unobstructed air stream. This more or less represents aircraft engine practice, but in motorcycle work, the chief field for air-cooling at present, the problem is complicated by the presence of mud-guards and similar obstructions. To place a complete motorcycle in a fan stream is no small order, and tests on the road with the aid of a side-car are hardly practicable with existing apparatus, since the galvanometers used in thermoelectric work are too delicate for use on a road vehicle. The writer has, however, made two tests in which an approximation to motorcycle conditions was attempted.

In the first a dummy cylinder was "blown at" by a fan in the usual manner, but a "mud-guard" was interposed, as shown in Fig. 12, the dimensions being approximately those of a typical 350 cm^3 single-cylinder engine. In Fig. 13 are given the results obtained under these conditions, those with the "mud-guard" removed being given for comparison. These results are distinctly surprising, particularly in the front of the cylinder, where the cooling is actually increased by the mud-guard. At the sides of the cylinder the cooling is decreased, while at

the rear it is unaltered. The lower (dotted) curve shows a test made with the actual motorcycle, on which the above "model" was based, the machine being placed head on to the wind in an open field. This test is, of course, extremely rough, especially as the wind was rather gusty, but the general characteristic appears more or less the same as in the "bench" test. This method has distinct possibilities, since it avoids the heavy cost of "blowing at" a complete machine, but hitherto the writer has not had an opportunity of seriously trying it out.

Future Developments

Both air and land transport offer a wide scope for investigations of this type. In the radial aircraft engine the cooling problem is relatively simple, and has been thoroughly studied, but of other types, such as the Vee, much less is known, and there are many possibilities to be explored. The motorcycle field is practically virgin ground, and present practice appears to be purely empirical, as is shown by the extraordinary diversity of cooling fin arrangements. The cooling of twin and multi-cylinder engines, in particular, well deserves study, likewise the effect of leg-shields and of cowling of various forms.

It is likely, moreover, that in the future unorthodox types of engine will be introduced, in which the cylinder position, and therefore the cooling problem, differs greatly from normal

practice. The development of such types would, it seems probable, be considerably simplified by experiment on these lines.

In conclusion, the writer would like to express his thanks to Messrs. Ricardo & Company for permission to publish these experiments, which were carried out at their Shoreham research laboratory.

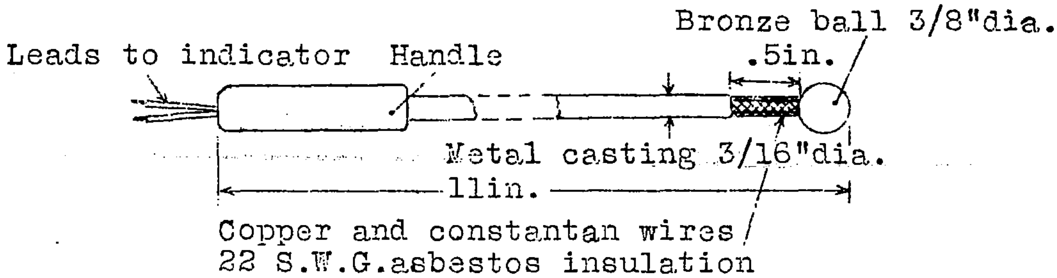
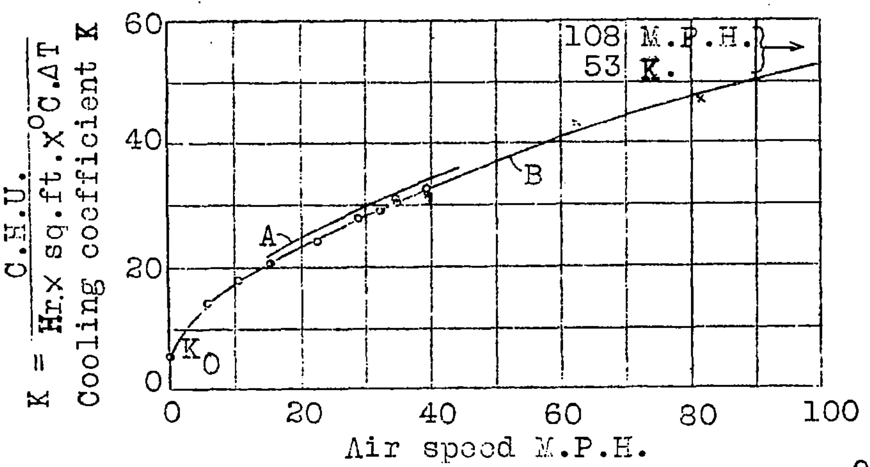


Fig.1 Ball type cooling meter.



Curve A = Wind tunnel $K=2.95\ V^{0.61}+K_0$

Curve B = Fan outlet $K=2.52\ V^{0.63}+K_0=6.0$

Fig.2 Calibration curve

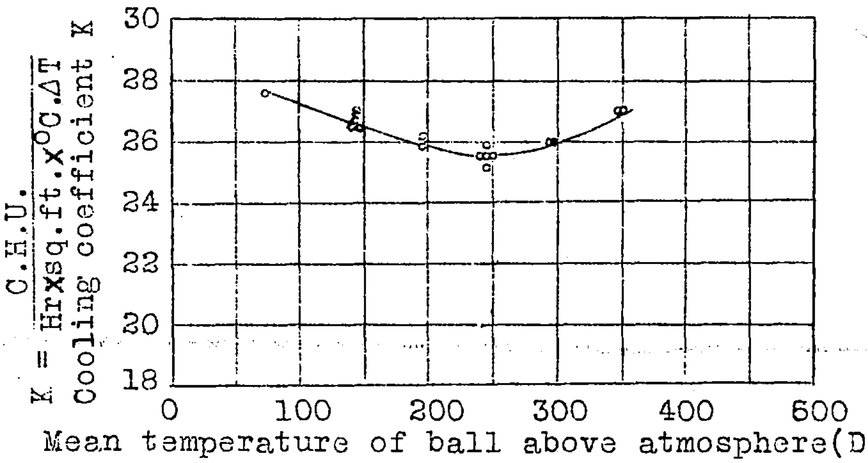
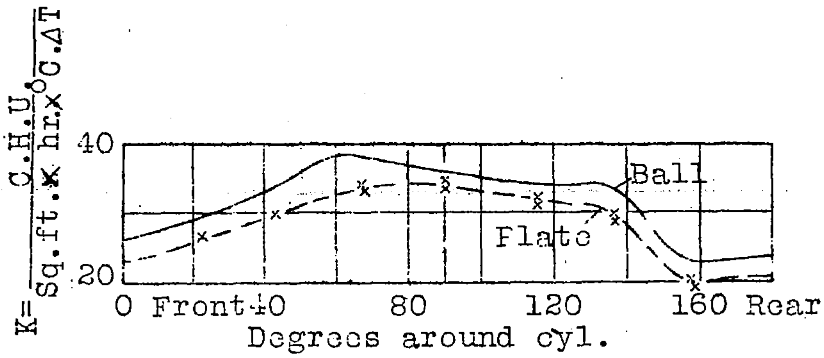
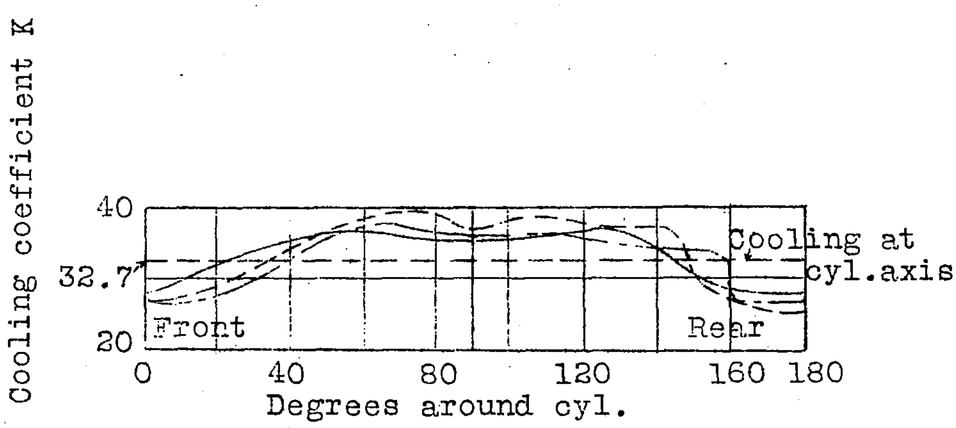


Fig.3 Effect of temperature on heat transfer coefficient. Wind speed (calculated)27 M.P.H.



——— Ball
– – – – Plate
Cooling around 7 in.unfinned cylinder.
0.4 in.clearance.Wind 35 M.P.H.at cylinder center.

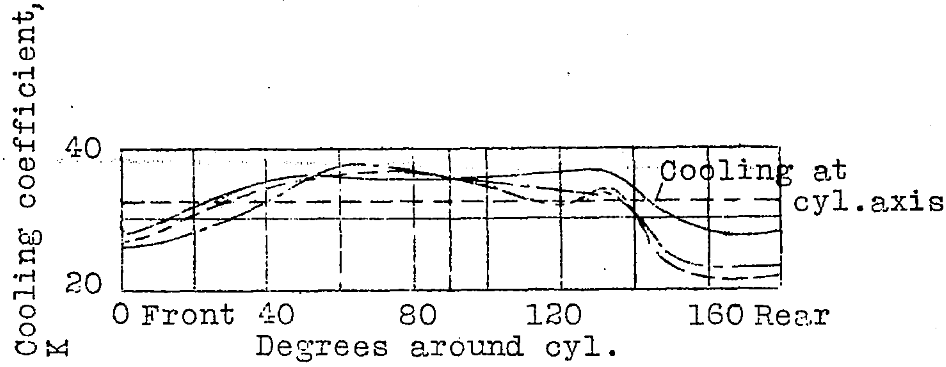
Fig.4 Comparative tests with ball and plate type meters.



Fan speed 1100 R.P.M.
Wind speed on cyl.axis with cyl.removed = 35 M.P.H.

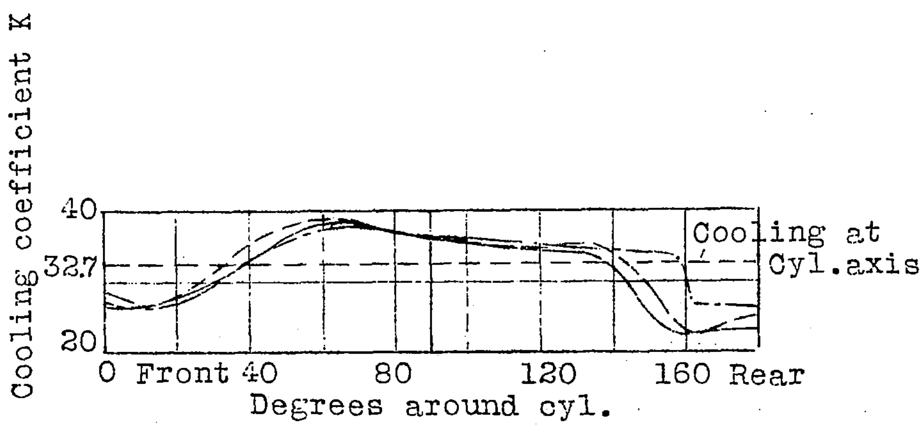
———	Cooling	meter	No.3	Ball,	2 in.	cyl.	0.4 in.	radial	clearance
– – –	"	"	"	"	4.4in.	"	0.9 in.	"	"
–·–·–	"	"	"	"	7 in.	"	1.4 in.	"	"

Fig.5 Cooling test on unfinned cylinders. Radial clearance = 0.2 x cylinder diameter.



Fan speed 1100 R.P.M.
Wind speed on cyl.axis with cylinder removed=35 M.P.H.
Cooling meter No.3 Ball,2 in.cylinder.
" " " " " 4.4in. "
" " " " " 7 in. "

Fig.6 Cooling tests on unfinned cylinders. Constant radial clearance = 0.4 in.



Fan speed 1100 R.P.M.
Wind speed on cyl.axis with cyl.removed=35 M.P.H.
Cooling meter No.3 Ball,0.4 in.radial clearance.
" " " " " 0.9 in. " "
" " " " " 1.4 in. " "

Fig.7 Cooling tests on unfinned cylinder 7 in.dia. Radial clearance = 0.4,0.9,1.4 in.

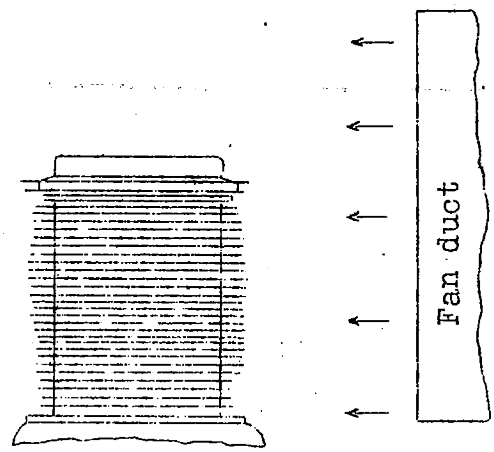


Fig.8 Diagram showing relative positions of cylinder and fan duct.

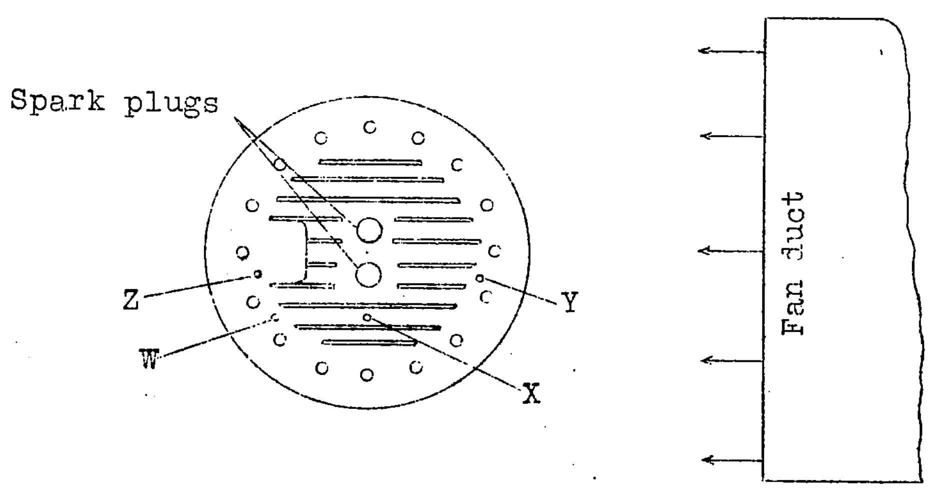
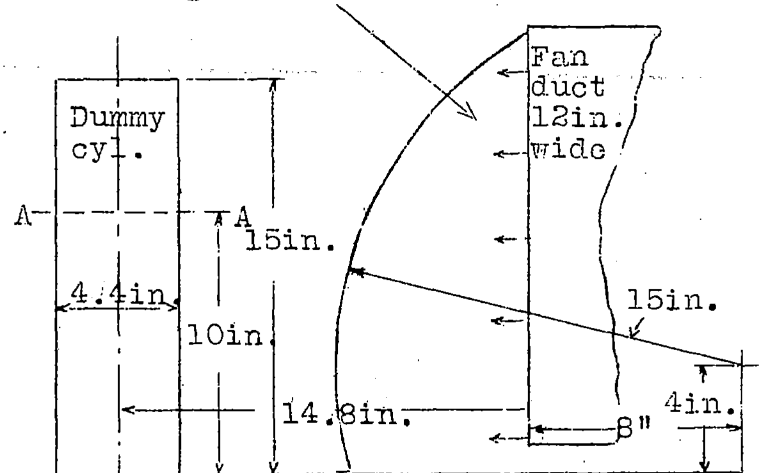


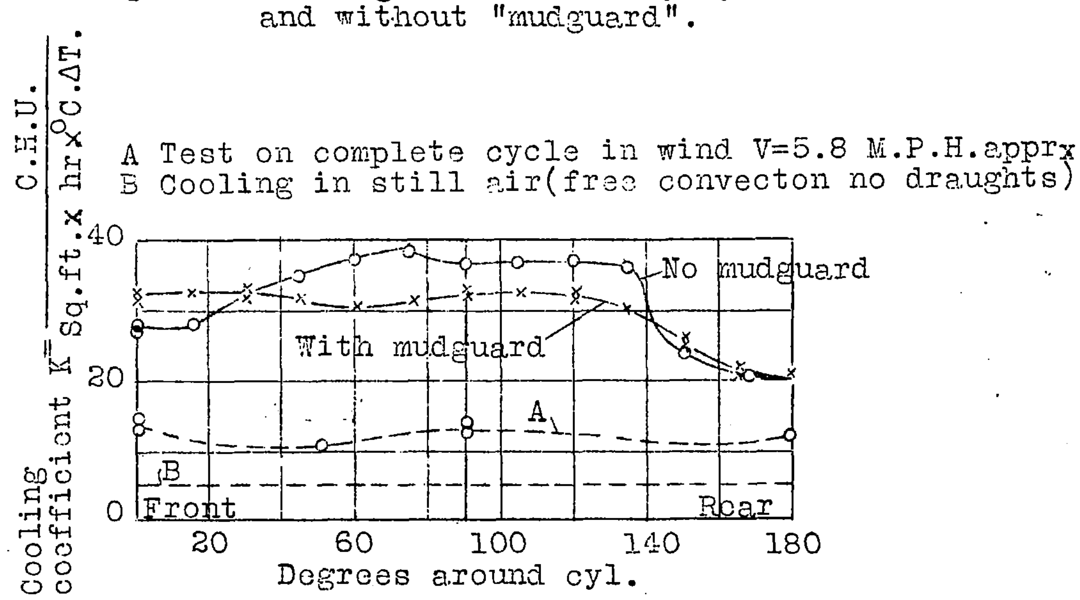
Fig.9 Plan view of cylinder head and fan duct.



A A Level at which cooling tests were made

Relative position of cylinder and mudguard as in Beardmore B & S cycle.

Fig.12 Cooling tests on dummy cylinder with and without "mudguard".



Test on dummy cylinder with wind obstructed by mudguard.
Wind speed at cylinder center-line with cyl.removed (no mudguard)=35 M.P.H.
Dummy cyl. 4.4in.dia. Radial clearance from surface of cyl. to center of ball = 0.4in.(no fins).

Fig.13 Cooling meter ball.